(5)

Report No. 8205-X4300-200

FINAL REPORT
F49620-81-C-0021
EXPERIMENTAL INVESTIGATION OF NEUTRAL PLASMA BEAM PROPAGATION ACROSS A MAGNETIC FIELD

Submitted to

Air Force Office of Scientific Research
Bolling AFB

By

AMAF Industries, Inc.
P.O. Box 1100
103 Sterrett Building
Columbia, Maryland 21044

Carl Spight

Dr. Carl Spight
Principal Investigator
(301) 982-1585

AMAF Industries Incorporated

2

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFOSR-TR- 82-0590	2. GOVT ACCESSION NO. A1-173	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Experimental Investigation of Neutral Plasma Beam Propagation Across a Magnetic Field		5. TYPE OF REPORT & PERIOD COVERED Final Report - Year One 02/15/81 - 02/14/82
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Dr. Carl Spight		8. CONTRACT OR GRANT NUMBER(s) F49620-81-C-0021
9. PERFORMING ORGANIZATION NAME AND ADDRESS AMAF Industries, Inc. P.O. Box 1100 Columbia, Maryland 21044		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2301/A7
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Office of Scientific Research Building 410 Bolling AFB, DC 20332		12. REPORT DATE April 14, 1982
		13. NUMBER OF PAGES 46
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Diagnostic, Current, Magnetic Field, Plasma

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(See Next Page)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

ABSTRACT

The conversion, described herein, of a pre-existing Hypervelocity Plasma Generator Facility to operate in a regime of importance to particle beam research has been completed. The facility is now capable of producing a plasma flow-magnetic field environment that in a scaled manner simulates the exoatmospheric propagation of a plasmoid across the geomagnetic field. A full set of flow and field diagnostics have been implemented and calibrated. It includes magnetic field probes for the slowly varying transverse background and the fast varying motionally induced fields, a laser schliren system for monitoring density gradient structure of the beam and time-of-flight fast photodiode probes for beam velocity measurements. Port access is available for monitoring directly electrostatic or electromagnetic fields associated with beam propagation. In tandem with experimental activity a theoretical analysis effort has been initiated, in interaction with theoreticians at Los Alamos National Laboratory, which intends a significant contribution to the stability analysis of a bounded plasma beam which can exhibit polarization and/or diamagnetic effects. No satisfactory theory or numerical simulations are currently available for that intrinsically three-dimensional dynamics.

TABLE OF CONTENTS

INTRODUCTION

There is an extensive literature, spanning more than four decades, describing investigations of spatially localized streams or plasma-magnetic field entities (plasmoids) in interaction with background magnetic field environments. Those investigations include theoretical analyses, computer simulations, and experimental research efforts. The large fraction of these investigations, however, have concerned plasma interactions characterized by $M_A \lesssim 1$, where M_A is the Alfven mach number defined such that:

$$M_A^2 = (\text{plasma flow velocity/Alfven speed})^2$$
$$= (\text{plasma kinetic energy density})/(\text{magnetic field energy density})$$

It is well established that in such regimes, the plasma is either strongly decelerated (and/or trapped) by the transverse magnetic field or propagates unimpeded (only after undergoing charge polarization effects) at the reduced ExB drift velocity. Very little work has been done in the "super-Alfvenic" regimes: $M_A >> 1$. This is the regime of critical importance in the exoatmospheric propagation of very energetic neutralized charged particle beams. Recent computer simulations in that regime (e.g., those of the theory group effort at Los Alamos National Laboratory (LANL)) have shed some light on propagation dynamics but have been handicapped by the following limitations:

a. The lack of any clearly justifiable choice criteria for selecting among the many possibilities for collective mode instabilities in that growth rates depend critically upon assumed initial plasma flow structures.

b. The computational complexity and time intensivity of full three-dimensional simulations necessary to treat correctly the boundary effects which are inescapable in actual beam propagation.

c. The limited ability to follow the plasmoid for long (simulation) propagation distances (related to computer memory size/computation time limitations) and/or the inability to choose rationally among possible computation box boundary conditions.

d. An absence of knowledge of the significance of nonlinear processes in either saturating linearly growing instabilities or aggravating their effect.

Associated theoretical efforts have almost always been restricted to linearized treatments and/or have assumed (for tractability) highly simplified geometries.

It that light, a carefully organized set of scaled simulation <u>experiments</u> can thus provide important new knowledge which can support and complement the theoretical and computer simulation efforts. This is the significance of the effort supported by the contract (F49620-81-C-0021) now ended. The experimental facility which was used is located at Morehouse College, Atlanta, Georgia and was made available to AMAF Industries, Inc. on a leased basis.

STATEMENT OF WORK

The research objectives for the effort as proposed were defined by the following tasks (see Appendix A for the Statement of Work as it actually appeared in the contract document):

1. Establish effective channel of communications with existing computer simulation groups (e.g., LASL).

2. Review published literature on experimental and theoretical research on instabilities in the plasma flow regime $M_A \gtrsim 1$ for applicable insights.

3. Reconfigure existing hypervelocity plasma flow generator facility to operate with high reproducibility in the regime $M_A >> 1$ as well as $M_A \gtrsim 1$.

This will involve (as simple engineering tasks):

a. Extension of the vacuum chamber in the flow direction by addition of a four-foot pyrex glass pipe section.

b. Redesign and reconstruction of the magnetic field producing coil system (currently a Helmholtz pair) to produce an approximately uniform field over the extended flow channel.

c. Addition of a ballast chamber, a precision leak valve, a mechanical vacuum pump, and a vacuum gauge to supply controllable quantities of selected gases to the breech of the gun (operating in the gas "puff" mode).

4. Construct and calibrate fast response magnetic, electric and current probes for flow diagnostics (designed by well-known techniques, to have response time $\lesssim 0.1\,\mu$sec).

5. Procure and bring to operational status a fast optical system (image converter or Kerr optics) for macroscopic structure observations.

6. Begin program of experimental parmetric surveys (with full diagnostic monitoring):

a. Plasma beam velocity.

b. Plasma beam density.

c. Plasma beam particle mass (variations in composition).

d. Propagation chamber ambient pressure.

e. Background magnetic field intensity.

f. Background magnetic field structure.

7. Analyze results of experimental surveys as to:

a. Dependence of propagation stability on parameter values.

b. Characteristic of instability structure (growth rates, spatial scales, onset conditions, saturation levels).

8. Summarize results in form for inclusion in computer simulations (especially in computer simulation areas a. and d. described previously).

9. Investigate experimentally (guided by appropriately modified LASL computer code predictions as they become available) possible means for stabilizing the propagating beam with an aim of achieving the highest energy ir the beam consistent with stability.

STATUS OF THE RESEARCH EFFORT

THE FACILITY CONVERSION:

The facility utilized was located in the Department of Physics at Morehouse College in Altanta, Georgia. It had previously been used in a Department of Energy sponsored research effort in pulsed, inductive direct energy conversion based on radial expansion flows. The major components of the system are:

1. The coaxial plasma gun and associated capacitor bank.

2. The magnetic field coil system and associated capacitor bank.

3. The vacuum chamber and associated pumps.

4. Plasma and field diagnostics.

5. The data acquisition/control room.

A large area view of the above-table-top-visible portion of the facility is provided in Figures 1a and 1b.

1. The Coaxial Gun and Capacitor Bank

The coaxial plasma gun is a standard Marshall gun configuration capable of being either metallic foil or gas "puff" breech loaded. In the gas "puff" mode it is loaded by a thyratron controlled, solenoid actuated gas valve. The gun is constructed of copper outer and brass rod inner electrodes with an outer radius/inner radius of 4 and a length of 10 cm. The plasma composition options include He, N, A, or various metals (from foils). Details of the construction of the gun is provided in Figures 2a and 2b. The capacitor bank for the gun is comprised of 8 capacitors rated at 15 uf and 20 KV in parallel yielding a maximum storage of 24 kilojoules. The energy in the bank in switched by 4 type GL-7703 ignitrons in parallel (Figure 3). The capacitor bank switched into the gun has a "ring" frequency of approximately 10 kHz. A typical storage oscilloscope trace of the gun voltage is shown in Figure 4. Nominal plasma densities and flow velocities are respectively $10^{22} m^{-3}$ and 10 km/sec. Figure 5 is an open shutter photograph of the beam.

2. The Magnetic Field Coil System and Capacitor Bank

The transverse magnetic field is produced by a rectangular coil array extending most of the length of the vacuum chamber. The coils are visible in Figures 1a and 1b. The coils consist of 4 turns each and are 145 cm long, 30 cm wide and are separated by 25 cm. The array has an effective inductance of approximately 100 uh. The array is powered by a capacitor bank comprise of 4 capacitors in parallel each rated at 60 uf and 20 KV. The bank is switched by 4 type GL-7703 ignitrons in parallel.

The calculated field profiles (normalized to the field at the array center) are plotted in Figures 6a and 6b for the orientation: x, width; y, length; z, separation. Figure 7 shows the array location on the vacuum chamber. The capacitor bank "dumps" into the array with a pulse (critically damped) that peaks in 200 usec and zeroes in 500 usec. Figure 8 shows a typical field signal as picked up by a magnetic field probe at the array center. With 3 KV on the bank, the field at the center is measured to be approximately 0.05 weber/m^2 (500 gauss). The field is proportional to the bank charge voltage over a large range of initial charge. An estimate of the fields required to operate in the $M_A \gg 1$ regime is calculated in Appendix D.

3. The Vacuum Chamber and Pumps

The vacuum chamber is constructed out of 6" diameter Corning pyrex sanitary drain pipe sections with rubber gaskets. Figure 9 shows the overall dimensions of the chamber. The gun is mounted on the axis of the "T" end. The chamber is pumped by a large, two-stage mechanical pump (Welsh 1397) and a small oil diffusion pump with backing pump to the 1-10 uHg range.

4. Plasma and Field Diagnostics

The background and short time-scale magnetic fields are measured by magnetic probes connected to passive RC integrators. Figure 10 shows such a probe inserted through an access port into a crossed-T section. A typical calibration for such a probe working into a 100 usec RC integrator is 0.5 mV/gauss (5 V/weber/m^2).

The plasma velocity is measured by "time-of-flight" techniques using a bifurcated light pipe and a very fast response photodiode detector (Tropel). Figure 11 shows the setup and Figure 12 shows the location of the velocity probe as well as the field probe on the chamber.

The density gradient structure of the beam is measured by a laser schliren system (Kiefer & Lutz, 1965) with a 2 m travel path and using a 5 mwatt helium-neon laser as a source. The geometry of the setup is shown in Figure 13 and portions of the actual system are shown in Figures 14a, 14b, and 14c. In this system the voltage from the photodiode detector is proportional to the plasma (local) density gradient.

A fast optical Kerr cell shutter system has been designed and constructed but is not yet operative. This system will be used to obtain very short time interval photographs (100 nsec) which will catch the beam at early times in its propagation and allow for analysis of the mode structure of any dynamic instabilities.

5. The Data Acquisition/Control Room

The control room is completely enclosed by a double screen shielded room. Figure 15 shows the back of that enclosure and the BNC data/signal ports. The control room instrumentation includes 4 Tektronix storage oscilloscopes (Figure 16a) for data monitoring. Precisely controllable trigger signals are generated by the combination of a Tektronix 161/162 signal generator and an Abtronics Model 100 4 channel time delay generator (Figure 16b).

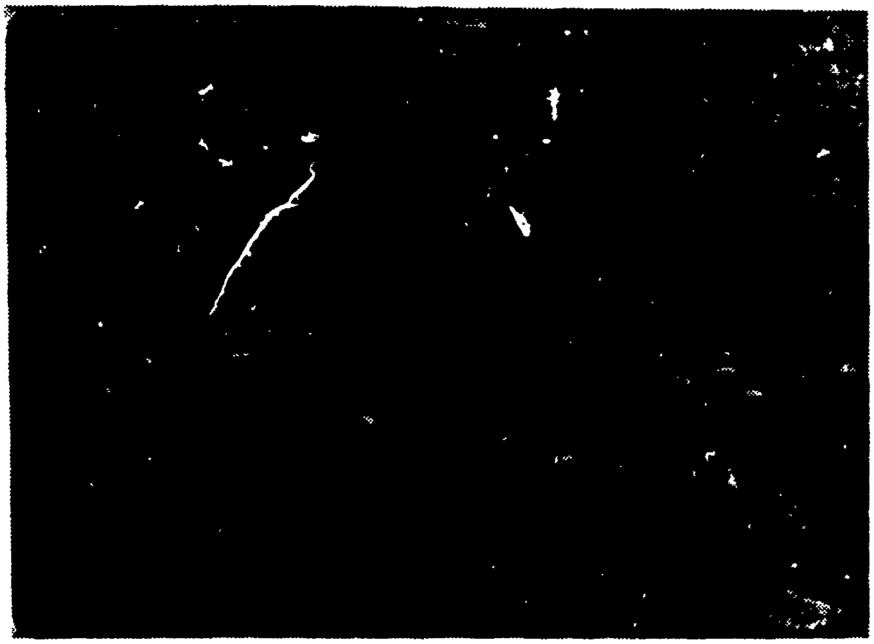


Figure 1a

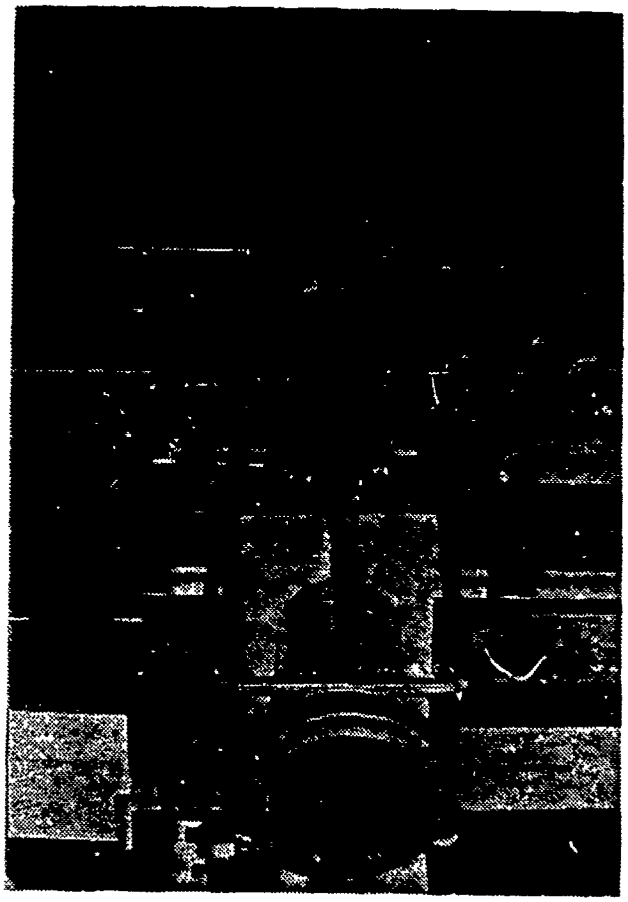


Figure 1b

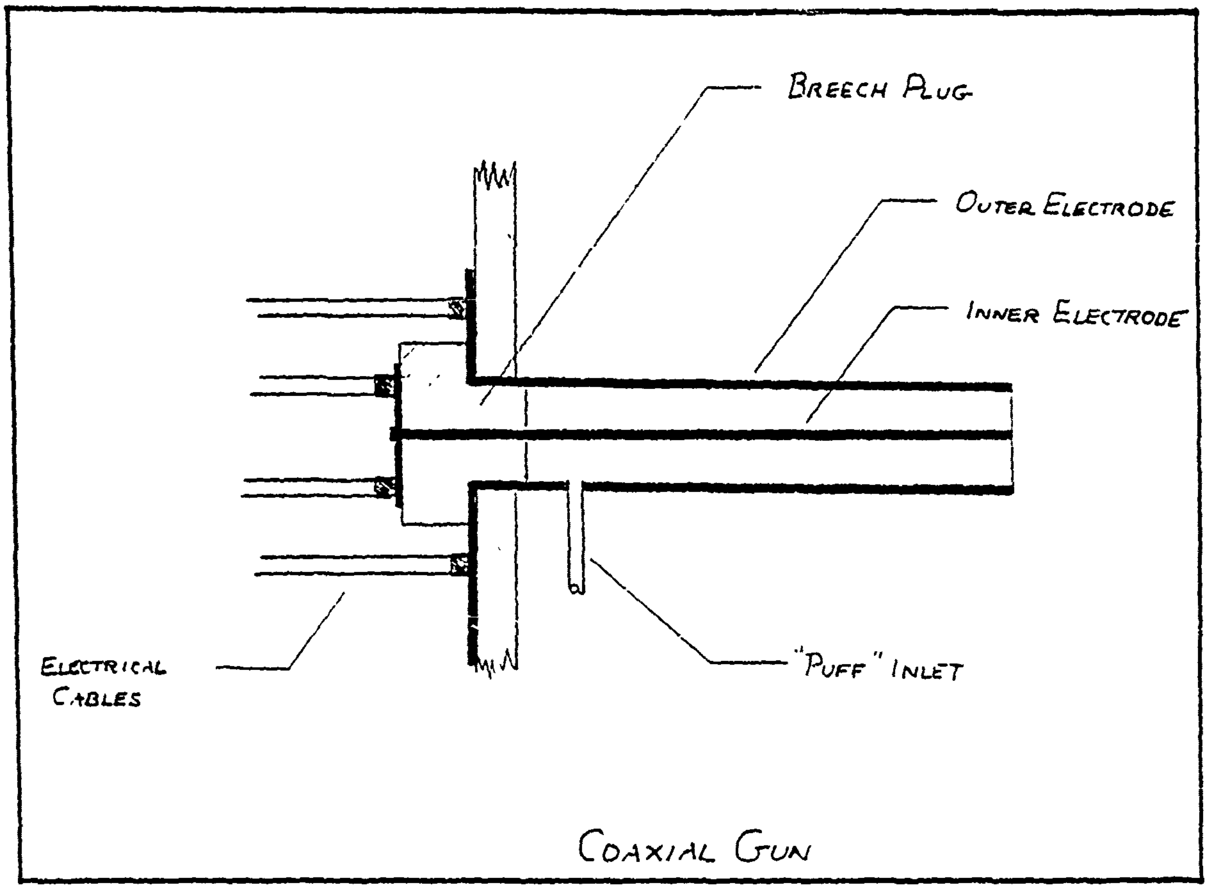


Figure 2a

Figure 2b

Figure 3

Figure 4

Figure 5

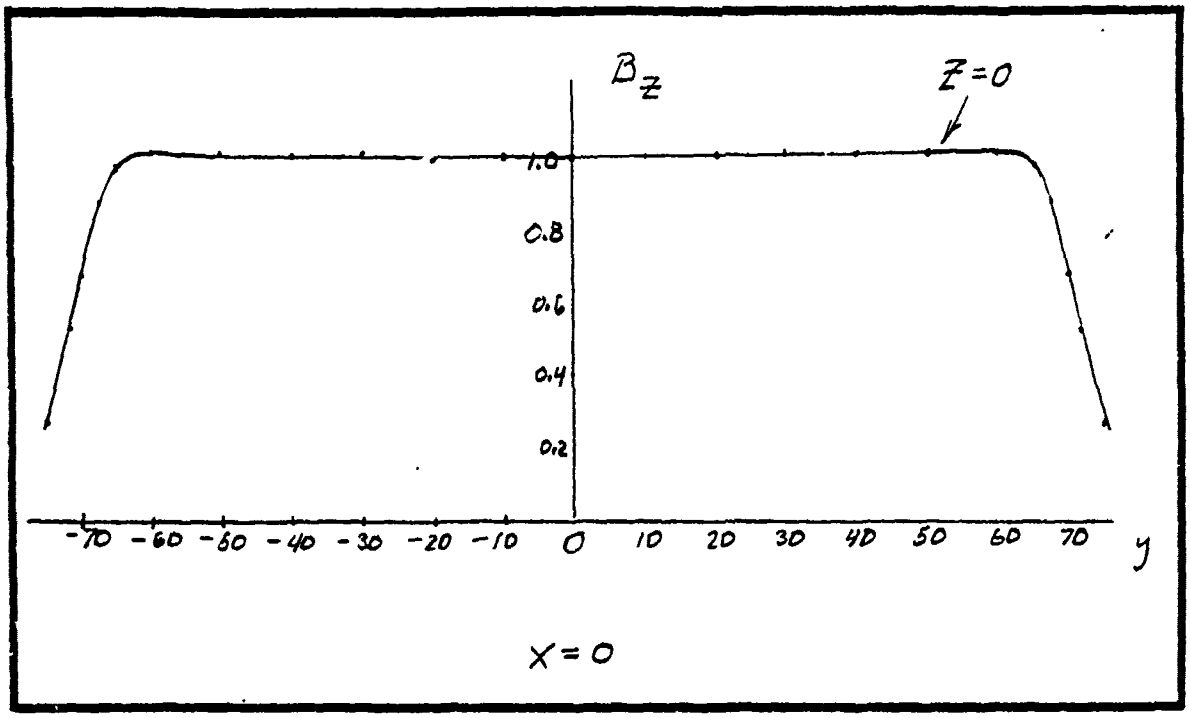


Figure 6a

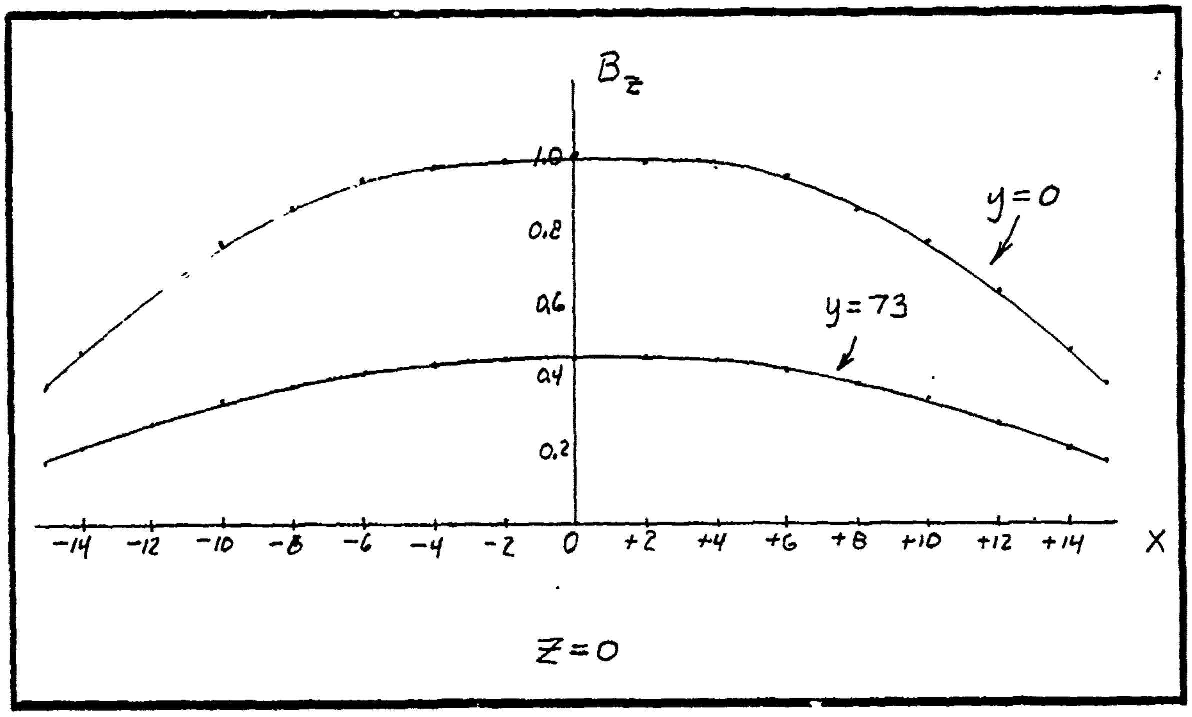


Figure 6b

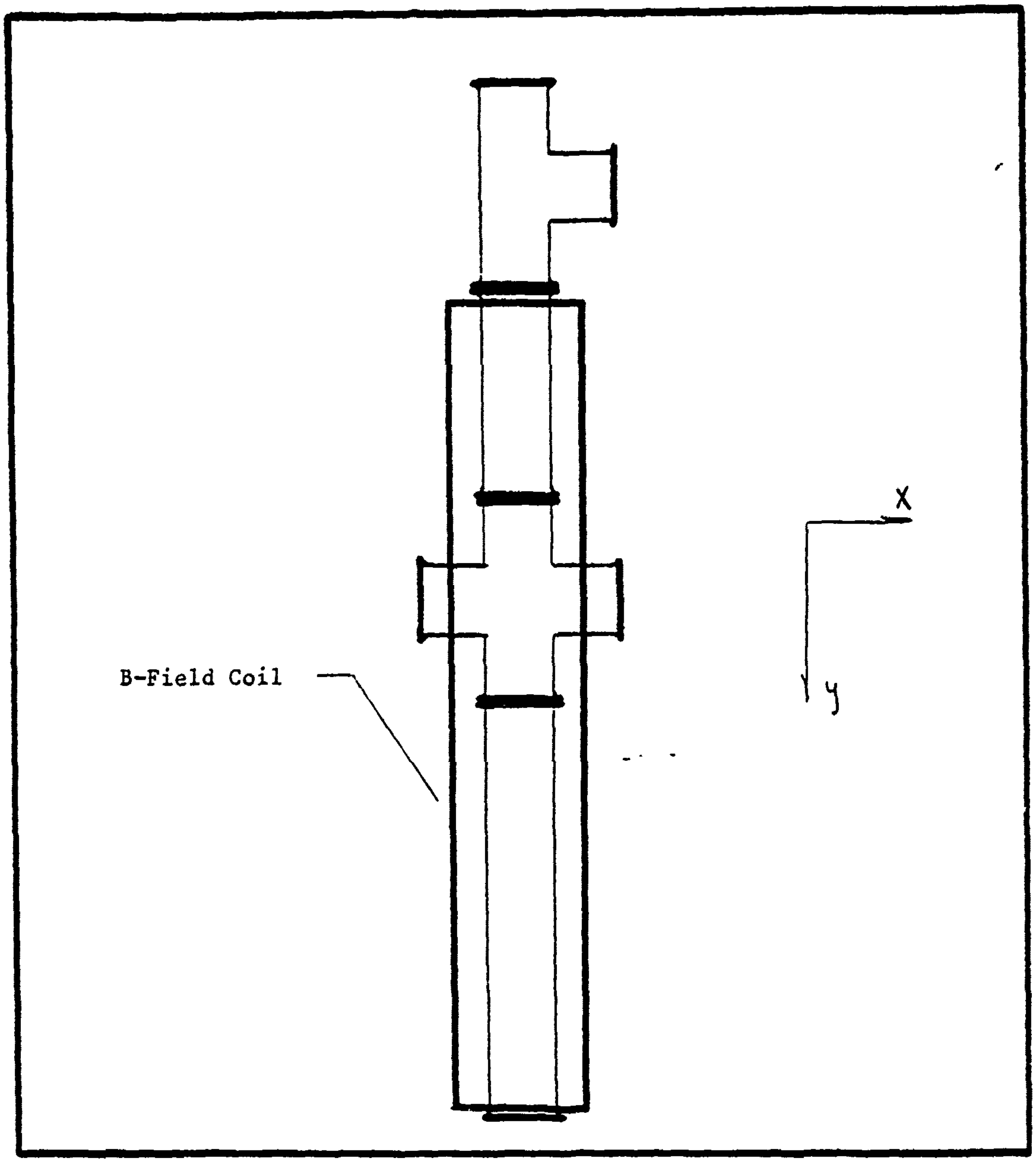


Figure 7

Figure 8

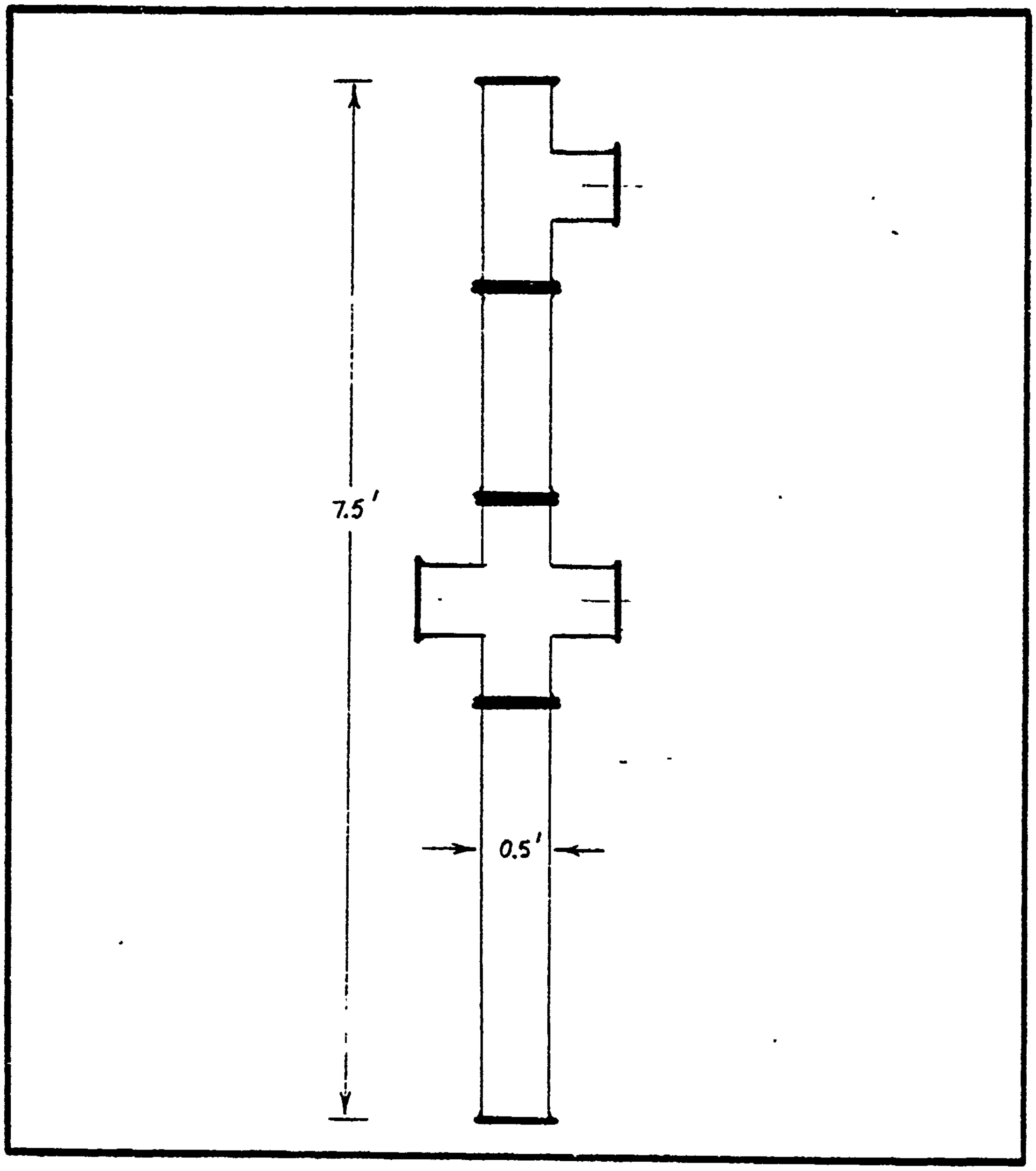


Figure 9

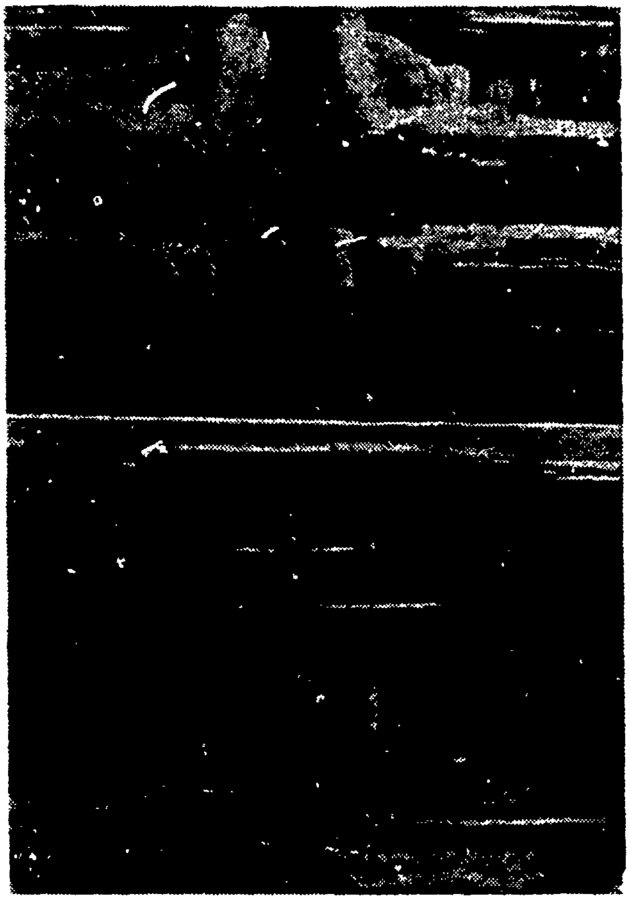


Figure 10

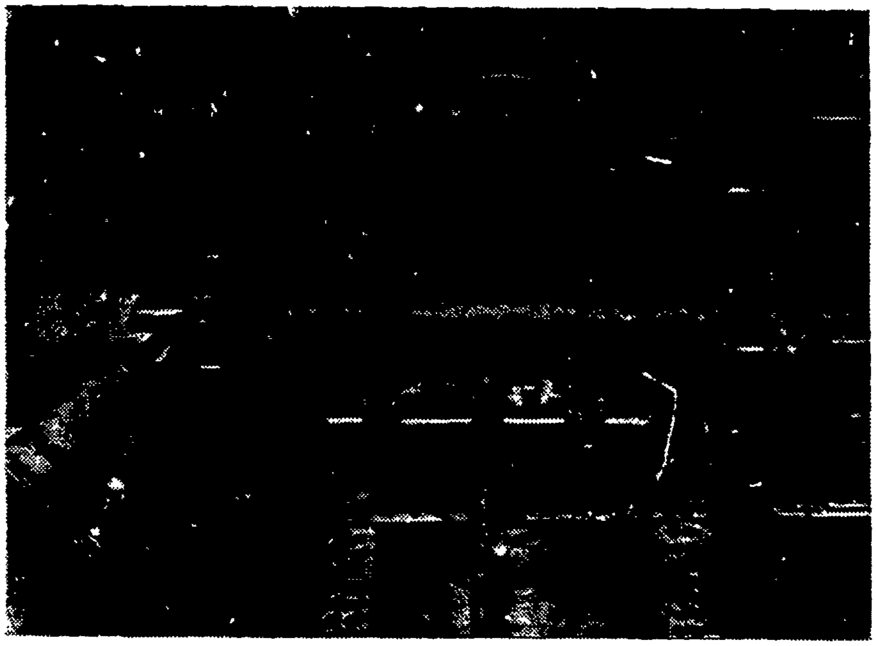


Figure 11

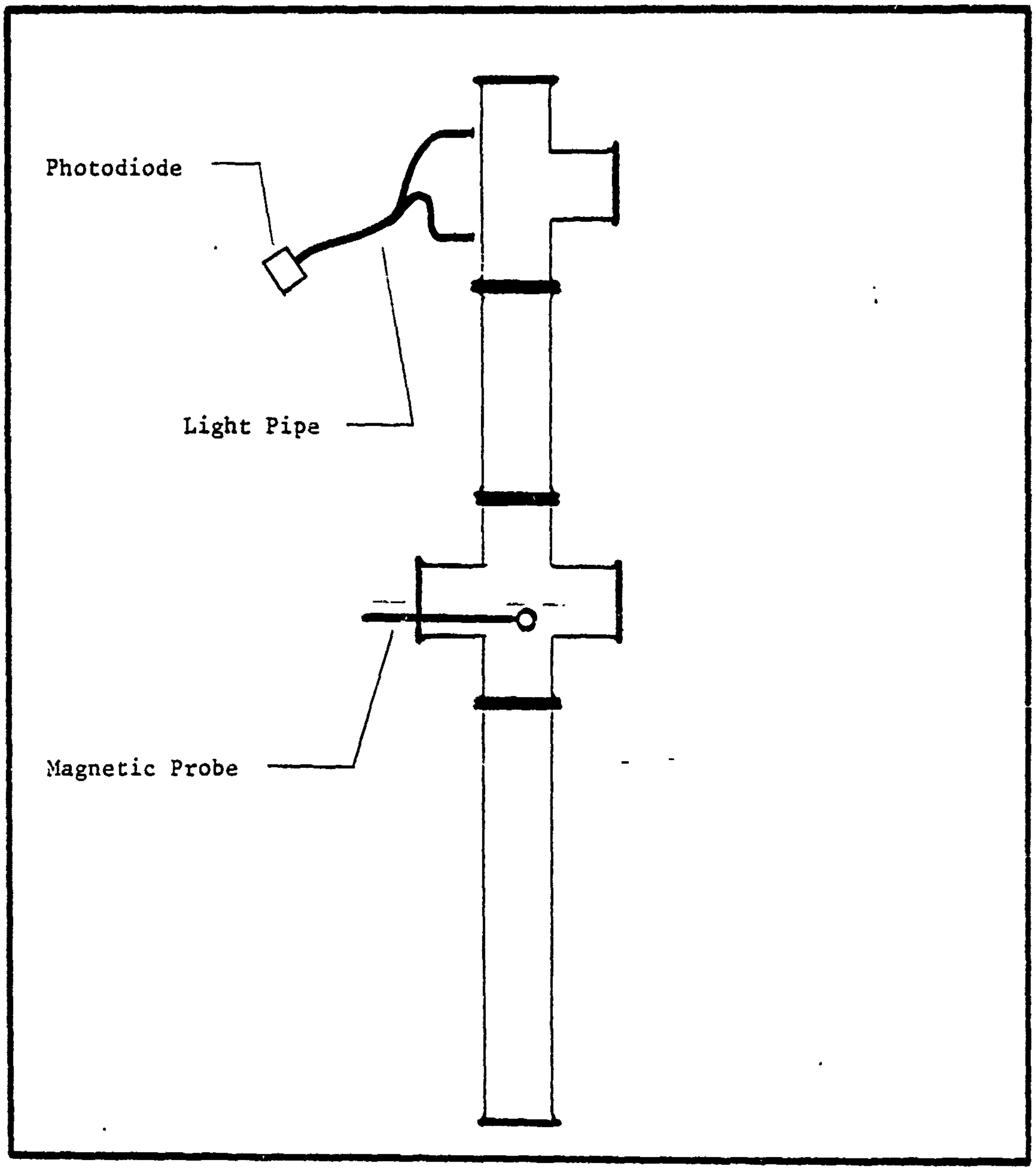


Figure 12

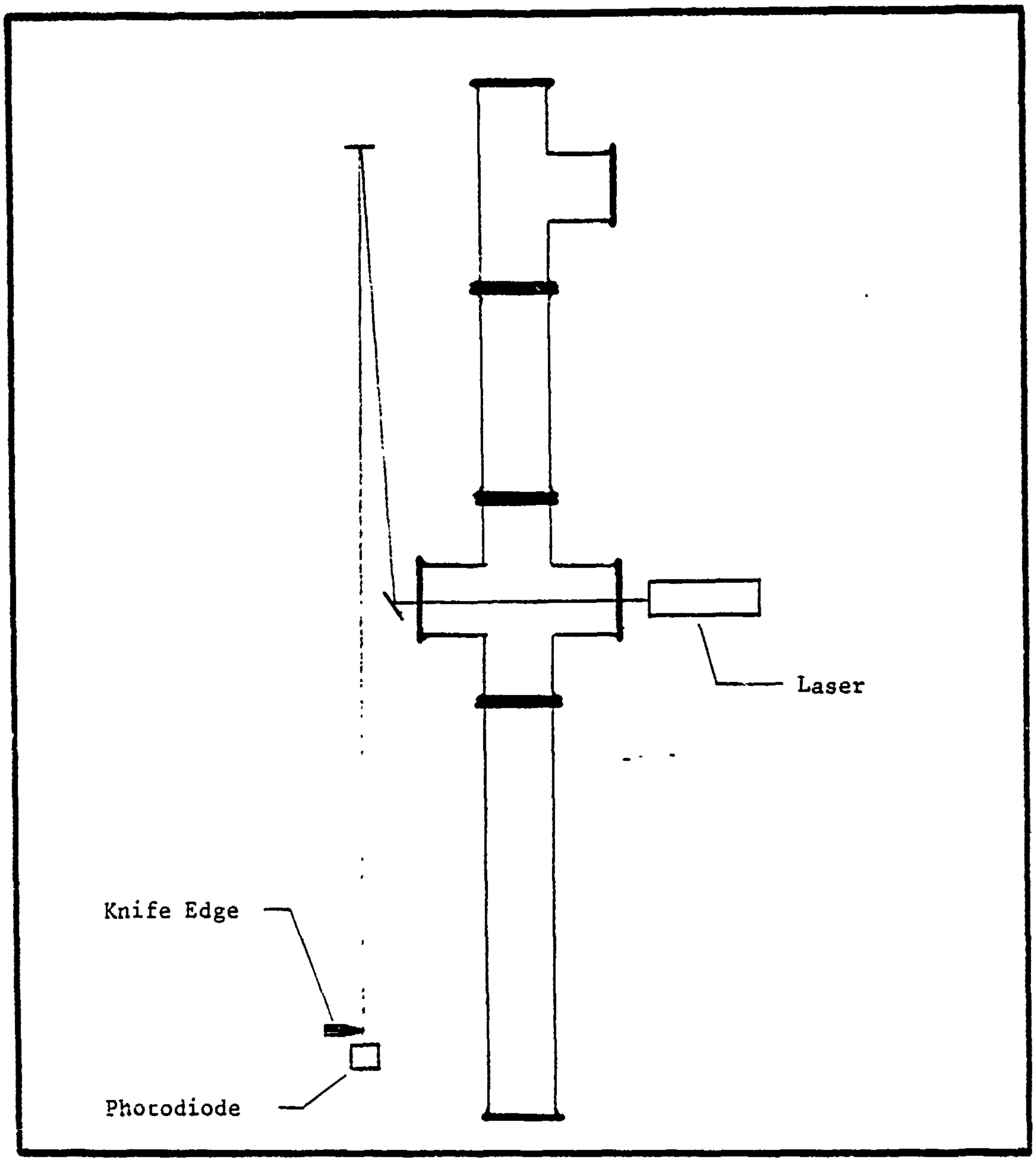


Figure 13

Figure 14a

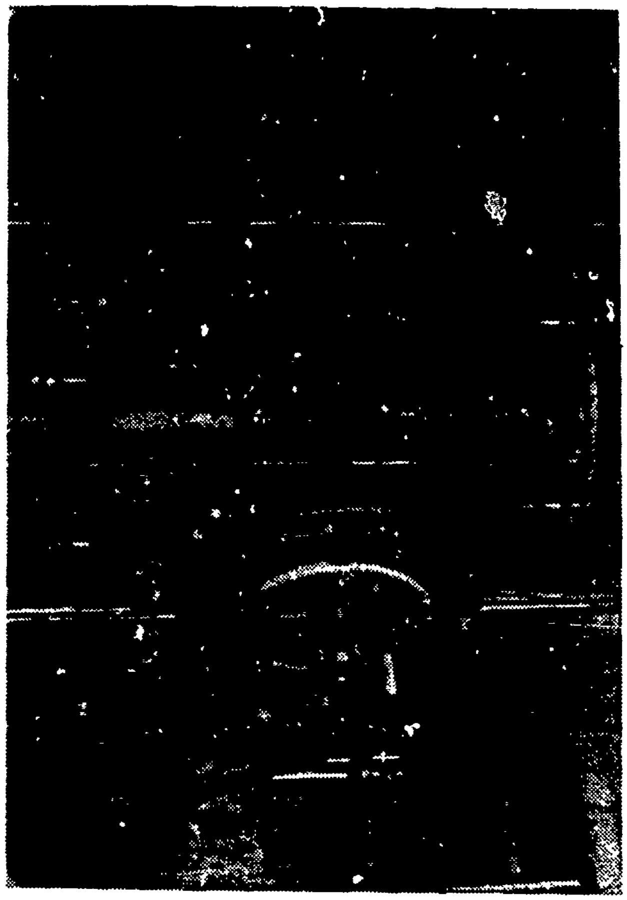


Figure 14b

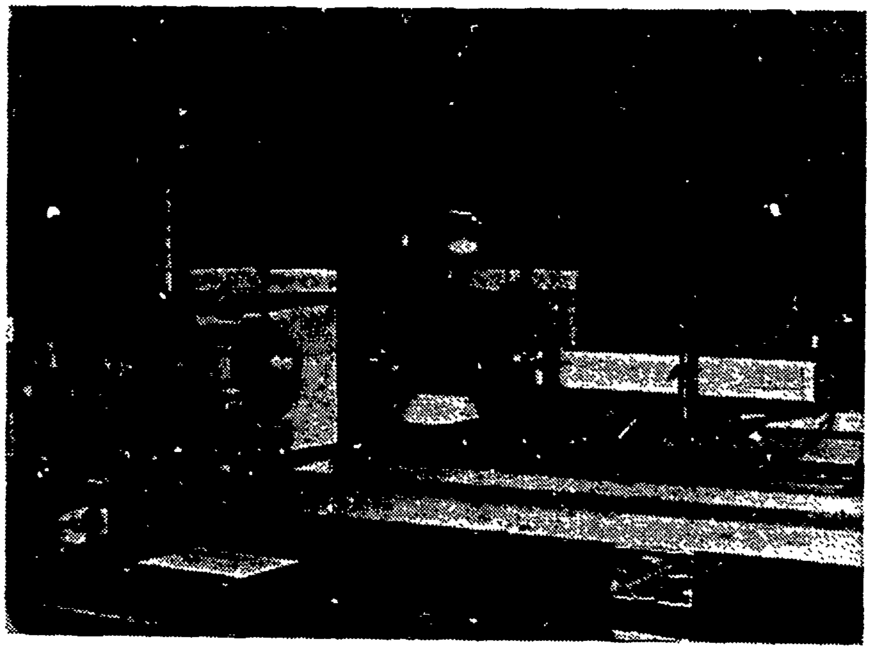


Figure 14c

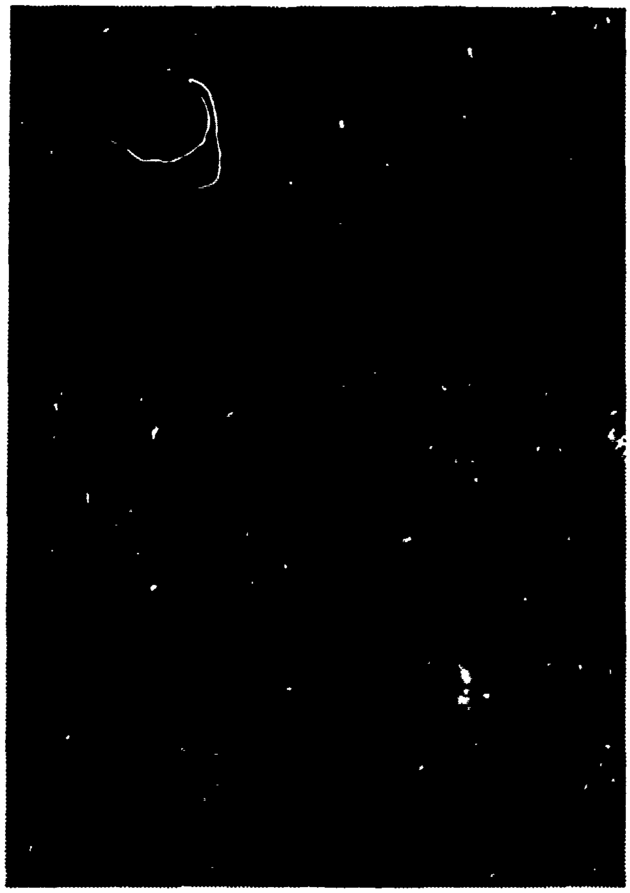


Figure 15

Figure 16a

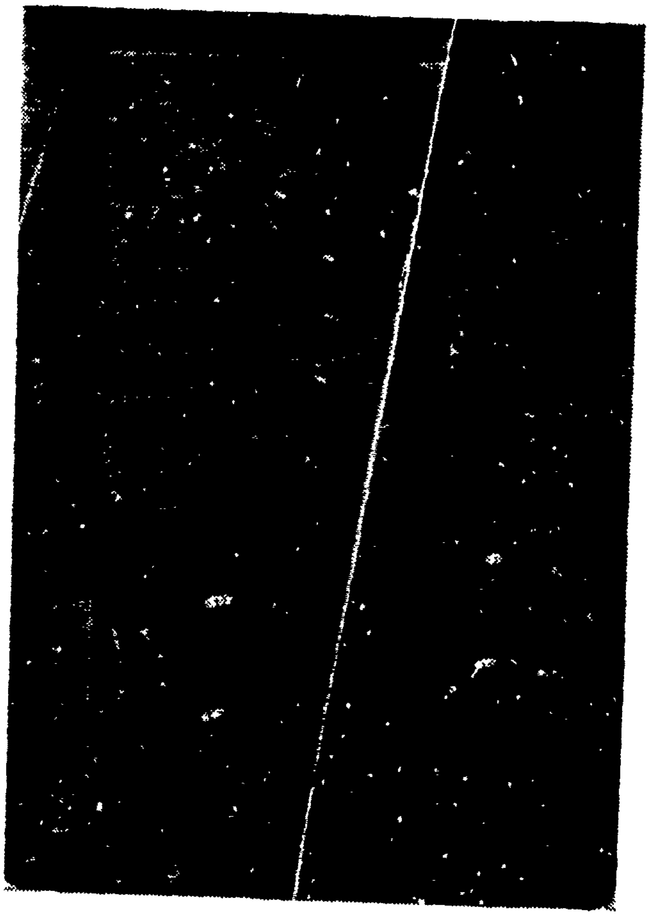


Figure 16b

STATUS OF THE EXPERIMENTAL EFFORT:

Tasks 1-4 of the Work Statement have been completed as projected. Task 5 (re the fast optical system) is still in a design implementation and testing phase. Task 6, the experimental parametric surveys, has just begun. Preliminary results appear to show propagation with little velocity attenuation, beam disruption, or magnetic field perturbation. This mode of propagation would be consistent with the analysis of Baker and Hammel (D. A. Baker and J. E. Hammel, "Experimental Studies of the Penetration of a Plasma Stream in a Transverse Magnetic Field," Physics of Fluids 8, 713 (1965)) where E x B motion plays a dominant role in propagation dynamics. It, however, is important to emphasize here that these results are only preliminary. A careful measurement of fast time scale magnetic processes during the field-flow intermixing region of the dynamics of propagation has yet to be done. Indeed, the first year of this effort has been necessarily expended in bringing the facility to the operational status where now such measurements can be done.

THE THEORETICAL EFFORT:

Although a great deal of theoretical analysis has been published on across-field propagation of plasma beams, the large majority of it has begun with assumptions (e.g., assumptions of polarized E x B steady states) which are precisely those that are of issue here. The theoretical work that we have found the most relevant: W. R. Shanahan,

"Energetic Neutralized Plasma Beam Propagation Across A Magnetic Field," Los Alamos Scientific Laboratory, LA-UR 81-2980, itself is significantly limited by simplifying assumptions. Moreover, the assumptions made limit the degree to which the analytical solutions derived therein could be valid. Indeed, we have not, even after careful analysis of the model for the propagation there presented, been able to come to the same mathematical results. We have initiated a dialogue with Dr. Shanahan to resolve these issues and to advance the quality of the theory. We propose, and have initiated, a more adequate theoretical analysis which takes the following into account:

1. The early time competition of diamagnetic and polarization (dielectric) response processes without making gross quasi-steady assumptions (a simple transverse dielectric constant, for example).

2. The possibility of large amplitude. nonlinear evolution of the field.

3. The critical importance of beam boundaries on beam propagation dynamics.

Such theoretical analysis will be critical to any experimental effort for interpretation of the data and for projecting corrective mechanisms should catastrophic instabilities be uncovered.

LIST OF JOURNAL PUBLICATIONS

There have been no journal publications resulting from the research as yet. It is anticipated that results of interest to the plasma physics community from both the experimental and theoretical efforts will be reported at the American Physical Society Plasma Divisional Meeting in November of 1982.

PROFESSIONAL PERSONNEL

Principal Investigator - Dr. Carl Spight
Responsible for overall research direction, technical validity, and project management.

Member of Technical Staff - Dr. Ronald Graves
Initially responsible for computer aided design of magnetic field coils and theoretical analysis.

Member of Technical Staff - Dr. Carlos Handy
Responsible for maintaining theoretical interaction with LANL and for pursuit of analysis of bounded plasma propagation.

Member of Technical Staff - Alfredo Monge
Responsible for execution of experiment in the plasma generator facility at Morehouse College, Atlanta, Georgia.

INTERACTIONS AND PRESENTATIONS

An effective channel for interaction in the theoretical effort has been established at Los Alamos National Laboratory (LANL) through Dr. William R. Shanahan of the Applied Theoretical Physics Division. That interaction has allowed us to clarify the strengths and limitations of his theoretical and numerical simulation analyses, to identify assumptions in that work of a problemmatic nature, and to define a reasonable direction for further theoretical analysis. Analysis of the stability of a bounded plasma beam with the inclusion of polarization effects has begun based on the insights gained through that interaction.

PROJECTIONS FOR FUTURE EFFORTS

Although the conversion of the hypervelocity plasma generator facility has been completed and a full set of diagnostics implemented, the year of effort has not, however, allowed time enough for meaningful data to be gathered on the stability properties of the beam in propagation across the applied field. Thus, a survey of beam dynamics as a function of gun and field parameters remains to be done. In addition, the absence of an adequate theory or numerical simulation of the fully bounded beam propagation regime points to the importance of bringing to closure the theoretical effort now underway. This will ensure that an analytic context will be available against which to make sense of the experimental data.

APPENDIX A

Contract Statement of Work (F49620-81-C-0021)

PART I - THE SCHEDULE

SECTION B - SUPPLIES/SERVICES AND PRICES

0001 RESEARCH

The contractor shall furnish the level of effort specified in Section F, together with all related services, facilities, supplies and materials needed to conduct the research described below. The research shall be conducted during the period specified in Section F.

0001AA

(1) Establish effective channel of communications with existing computer simulation groups, such as those at LANSL.

(2) Review published literature on experimental and theoretical research on instabilities in the plasma flow regime $M_A \gtrsim 1$ for applicable insights.

(3) Reconfigure Morehouse College hypervelocity plasma flow generator facility to operate with high reproducibility in the regime $M_A \gg 1$ as well as $M_A \gtrsim 1$.

This will involve (as simple engineering tasks):

(a) Extension of the vacuum chamber in the flow direction by addition of a four foot pyrex glass pipe section.

(b) Redesign and reconstruction of the magnetic field producing coil system (currently a Helmholtz pair) to produce an approximately uniform field over the extended flow channel.

(c) Addition of a ballast chamber, a precision leak valve, a mechanical vacuum pump, and a vacuum gauge to supply controllable quantities of selected gases to the breech of the gun (operating in the gas "puff" mode).

(4) Construct and calibrate fast response magnetic, electric and current probes for flow diagnostics (designed by well known techniques, to have response times 0.1 sec.).

(5) Perform experimental parmetric surveys (with full monitoring) of:

(a) Plasma beam velocity.

(b) Plasma beam density.

(c) Plasma beam particle mass (variations in composition).

d Propagation chamber ambient pressure.

e Background magnetic field intensity.

f Background magnetic field structure.

6 Analyze results of experimental surveys as to:

a Dependence of propogation stability on parameter values.

b Characteristic of instability structure (growth rates, spatial scales, onset conditions, saturation levels).

7 Summarize results in form for inclusion in computer simulations (especially in computer simulation areas a. and o. described previously).

8 Investigate experimentally (guided by appropriately modified computer code predictions as they become available) possible means for stabilizing the propagating beam with an aim of achieving the highest energy in the beam consistent with stability.

APPENDIX B

Milestone Chart

MILESTONE CHART

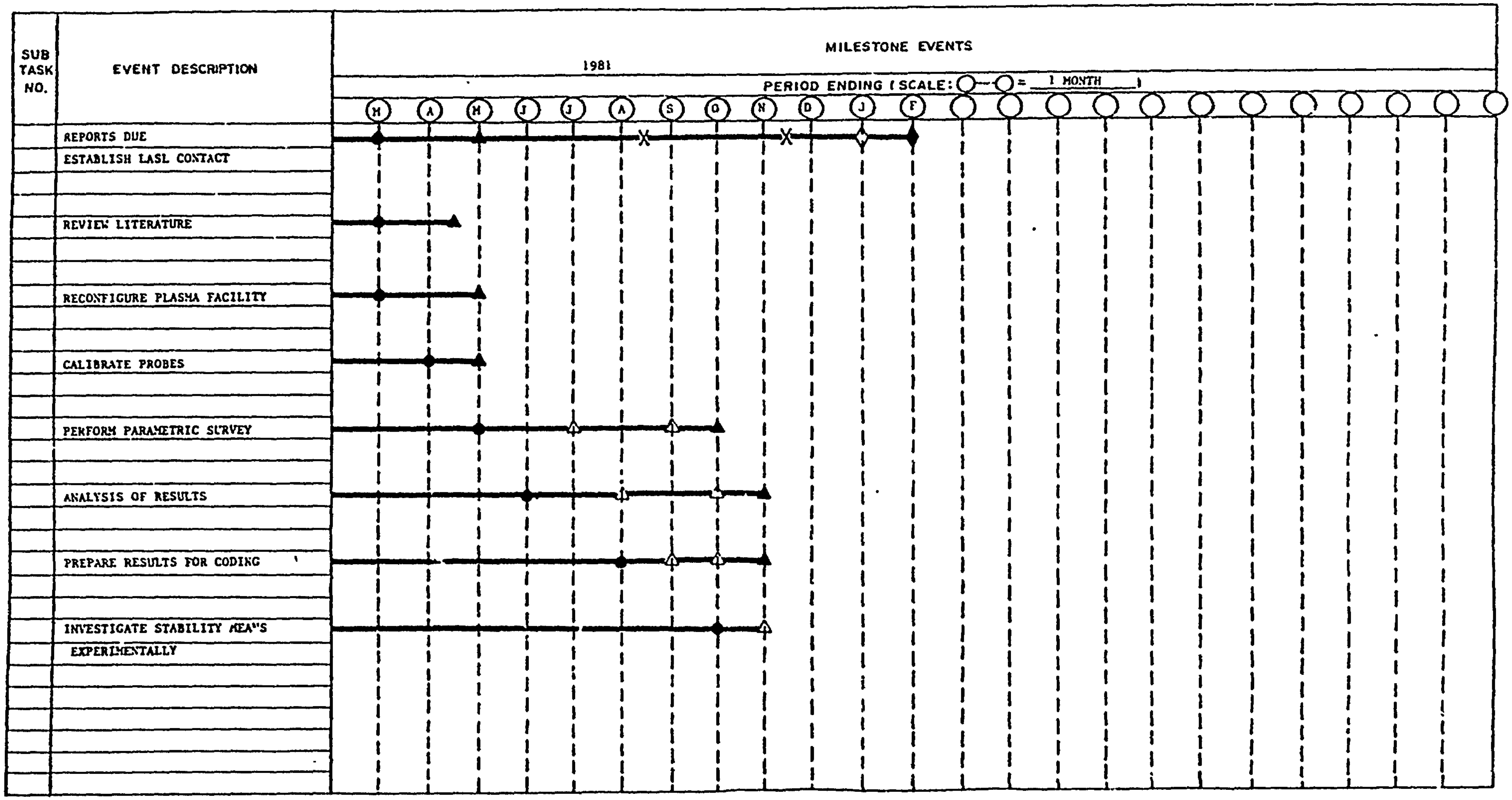
JOB DESCRIPTION EXPERIMENTAL INVESTIGATION OF BEAM PROPAGATION

JOB NUMBER 43

CUSTOMER AFOSR
CONTRACT NO. F49620-81-C-0021
DESCRIPTION EXPERIMENTAL PLASMA PHYSICS

NOTES
1.
2.
3.
4.

APPROVED
DATE MARCH 1981
REVISION



KEY:
- ● START
- △ INTERIM DELIVERABLE (DRAFT)
- ○ COMMENTS FROM CUSTOMER
- ▲ COMPLETION / DELIVERABLE
- × PROGRESS REPORT DUE
- ◊ FINAL REPORT DRAFT
- ♦ FINAL REPORT

PAGE__OF__PAGES

APPENDIX C

Source Program for Field Computations

LIS

CLFIELD 13:47EDT 05/10/82

```
* CURRENT LOOP MAGNETIC FIELD CALCULATION
*
INTEGER N,NX,NY,NZ
REAL SVECT(5,7),XMIN,XMAX,YMIN,YMAX,ZMIN,ZMAX,DX,DY,DZ,M(5),NORM
OPEN(FILE='PTFIL',UNIT=1,STATUS='UNKNOWN',ACCESS='LINENO')
CALL SCRSUP(SVECT,M,N)
CALL GRID(XMIN,YMIN,XMAX,YMAX,ZMIN,ZMAX,NX,NY,NZ,DX,DY,DZ)
NORM=1.0
CALL DFCALC(SVECT,M,0,0,0,0,0,0,1.,1.,1.,NX,NY,NZ,N,NORM)
CALL DFCALC(SVECT,M,XMIN,YMIN,XMAX,YMAX,ZMIN,ZMAX,DX,DY,DZ,NX,NY,NZ,N,NORM)
STOP
END
SUBROUTINE SCRSUP(SVECT,M,N)
REAL SVECT(5,7),M(5)
PRINT,'INPUT THE NUMBER OF SOURCE CURRENT LOOPS ';INPUT,N
I=1
DO 10 WHILE (I.LE.N)
PRINT,'INPUT CURRENT LOOP SOURCE ',I,' POSITION (XI,YI,ZI)'
INPUT, (SVECT(I,J),J=1,3)
PRINT,'INPUT CURRENT LOOP WIDTH(X) AND LENGTH(Y)'
INPUT, (SVECT(I,J),J=4,5)
PRINT,'INPUT CURRENT LOOP ',I,' STRENGTH(N*I)'
INPUT,M(I)
10 I=I+1
RETURN
END
SUBROUTINE GRID(XMIN,YMIN,XMAX,YMAX,ZMIN,ZMAX,NX,NY,NZ,DX,DY,DZ)
REAL XMIN,YMIN,ZMIN,XMAX,YMAX,ZMAX,DX,DY,DZ
INTEGER NX,NY,NZ
PRINT,'FIELD POINT GRID';PRINT,
PRINT,'INPUT MAX FIELD COORDINTES (X,Y,Z)';INPUT,XMAX,YMAX,ZMAX
PRINT,'INPUT MIN FIELD COORDINATES (X,Y,Z) ';INPUT,XMIN,YMIN,ZMIN
PRINT,'INPUT GRID RESOLUTION(DX,DY,DZ) ';INPUT,DX,DY,DZ
NX=(XMAX-XMIN)/DX+1
NY=(YMAX-YMIN)/DY+1
NZ=(ZMAX-ZMIN)/DZ+1
END
SUBROUTINE SCRPRT(SVECT,M,N)
REAL SVECT(5,7),M(5)
INTEGER N
PRINT,'SOURCE CURRENT LOOP FIELD INPUT PARAMETERS'
PRINT,;PRINT 100,
100 FORMAT(2X,'CURRENT LOOP',6X,'XI',8X,'YI',8X,'ZI',7X,'WIDTH',
&5X,'LENGTH',5X,'N*I'/)
PRINT 110,(I,(SVECT(I,J),J=1,5),M(I),I=1,N)
110 FORMAT(8X,I1,5X,5F10.4,F9.1)
RETURN
END
SUBROUTINE GRDPRT(XMIN,YMIN,XMAX,YMAX,ZMIN,ZMAX,DX,DY,DZ)
REAL XMIN,YMIN,XMAX,YMAX,ZMIN,ZMAX,DX,DY,DZ
PRINT,;PRINT,'FIELD GRID PARAMETERS'
PRINT,'XMIN = ',XMIN,' YMIN = ',YMIN,'ZMIN = ',ZMIN
PRINT,'XMAX = ',XMAX,' YMAX = ',YMAX,'ZMAX = ',ZMAX
PRINT,'DX = ',DX,' DY = ',DY,'DZ = ',DZ
RETURN
END
SUBROUTINE DFCALC(SVECT,M,XMIN,YMIN,XMAX,YMAX,ZMIN,ZMAX,DX,DY,DZ,NX,NY,
&NZ,N,NORM)
REAL SVECT(5,7),M(5),XMIN,YMIN,ZMIN,XMAX,YMAX,ZMAX,DX,DY,DZ,NORM
INTEGER NX,NY,NZ,N
```

```
700 REAL X,Y,Z,SPX,SPY,SPZ,INTG,I1,I2,I3,I4,XJ,YJ,ZJ,XL,YL,B(4)
710 CALL SCRPRT(SVECT,M,N)
720 CALL GRDPRT(XMIN,YMIN,XMAX,YMAX,ZMIN,ZMAX,DX,DY,DZ)
730 WRITE(1,500)
740 Z=ZMIN
750 DO 110 L=1,NZ
760 Y=YMIN
770 DO 100 I=1,NY
780 X=XMIN
790 DO 90 J=1,NX
800 B(1)=0;B(2)=0;B(3)=0
810 DO 80 K=1,N
820 SPX=SVECT(K,1);XJ=X-SPX
830 SPY=SVECT(K,2);YJ=Y-SPY
840 SPZ=SVECT(K,3);ZJ=Z-SPZ
850 XL=SVECT(K,4)/2
860 YL=SVECT(K,5)/2
870 I1=INTG(YJ,XJ,XL,ZJ,YL)
880 I2=INTG(XJ,YJ,YL,ZJ,XL)
890 I3=INTG(YJ,XJ,-XL,ZJ,YL)
900 I4=INTG(XJ,YJ,-YL,ZJ,XL)
910 B(1)=B(1)+ZJ*(I1-I3)
920 B(2)=B(2)+ZJ*(I2-I4)
930 B(3)=B(3)-(XJ-XL)*I1-(YJ-YL)*I2+(XJ+XL)*I3+(YJ+YL)*I4
940 80 CONTINUE
950 DO 120 II=1,3
960 120 B(II)=B(II)/NORM
970 B(4)=SQRT(B(1)**2+B(2)**2+B(3)**2)
980 IF(NORM.EQ.1.)
990 NORM=B(4)
1000 RETURN
1010 END IF
1020 WRITE(1,510) X,Y,Z,B
1030 500 FORMAT('0',5X,'X',10X,'Y',10X,'Z',10X,'BX',9X,'BY',9X,'BZ',
1040 &9X,'B'/)
1050 510 FORMAT(1X,3F10.2,4F11.3)
1060 90 X=X+DX
1070 WRITE(1,520)
1080 100 Y=Y+DY
1090 WRITE(1,520)
1100 110 Z=Z+DZ
1110 520 FORMAT(/)
1120 RETURN
1130 END
1140 REAL FUNCTION INTG(Q,P,P0,Z,UL)
1150 REAL Q,P,P0,Z,UL,B,C,D
1160 INTG=0
1170 B=-2*Q
1180 C=Q**2+(P-P0)**2+Z**2
1190 D=B**2-4*C
1200 IF(D.NE.0)
1210 DO 10 I=2,3
1220 INTG=INTG-(-1)**I*2*(2*UL+B)/D/SQRT(UL**2+B*UL+C)
1230 10 UL=-UL
1240 ELSE
1250 DO 20 I=2,3
1260 INTG=INTG-(-1)**I*0.05/(UL+B/2)**2
1270 20 UL=-UL
1280 END IF
1290 RETURN
1300 END


READY
```

APPENDIX D

Computation of Magnetic Field Limit

COMPUTATION OF MAGNETIC FIELD LIMIT:

CRITERION: $V/V_A \geq 10$

where V = PLASMA FLOW VELOCITY

V_A = ALFVEN SPEED

$= B/(\mu_0 MN)^{\frac{1}{2}}$

B = MAGNETIC FIELD STRENGTH

M = PLASMA PARTICLE MASS

N = PLASMA PARTICLE DENSITY

$\therefore B \leq V (\mu_0 MN)^{\frac{1}{2}}/10$

In MKS UNITS: $\mu_0 \sim 10^{-6}$

$M \sim 10^{-26}$

$N \sim 10^{22}$

$V \sim 10^{4}$

$\therefore B \leq 10^{-2}$ (10^{2} GAUSS)

APPENDIX E

Bibliography

BIBLIOGRAPHY

1. H. K. Moffatt and J. Toomre, "The Annihilation of a Two-Dimensional Jet by a Transverse Magnetic Field," Journal of Fluid Mechanics 30, 65 (1967).

2. CALSPAN Corporation, "Theoretical Analysis of Neutralized Beam Propagation," AFWL-TR-78-52 (1979).

3. E. Ott and W. Manheimer, "Cross-Field Injection, Propagation, and Energy Description of Intense Ion Beams with Application to Tokamak Plasma Heating," Nuclear Fusion 17, 1057 (1977).

4. Los Alamos Scientific Laboratory, "Preliminary Considerations Concerning Neutral Plasma Beam Propagation Across a Magnetic Field," LA-7954-MS/UC-34 (1979).

5. E. H. Beckner, "Flow of a Hydrogen Plasma Through a Transverse Magnetic Field," Physics of Fluids 7, 586 (1964).

6. J. Zorskie and W. H. Bastick, "The Interaction of Plasmoids with Magnetic Fields," Stevens Institute of Technology (AFO) SR68-1669/ SIT-P221 (6/68).

7. J. J. Lee, "Interaction of a Plasma Beam with a Magnetic Barrier," Case Western Reserve University, Technical Report A-65.

8. J. H. Kiefer and R. W. Lutz, "Simple Quantitive Schlieren Technique of High Sensitivity for Shock Tube Densitometry," Physics of Fluids 8, 1393 (1965).

9. W. Peter, A. Ron, and N. Rostoker, "Propagation of a Wide Ion Beam Into a Magnetic Barrier," Physics of Fluids 22, 1471 (1979).

10. Keiichi, et. al., "Propagation of Intense Ion Beams Across a Magnetic Field," J. Phys. Soc. Japan 46, No. 6, 1963 (1979).

11. S. Robertson, et. al., "Propagation of an Intense Ion Beam Transverse to a Magnetic Field," Physical Review Letters 47, No. 7, 508 (1981).